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FINAL REPORT

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## 1. Final Report

The high efficiency of energy generation inferred from radio observations of quasars and X-ray observations of Seyfert active galactic nuclei (AGNs) is apparently achieved only by the gravitational conversion of the rest mass energy of accreting matter onto supermassive black holes. Evidence for the acceleration of particles to high energies by a central engine is also inferred from observations of apparent superluminal motion in flat spectrum, core-dominated radio sources. This phenomenon is widely attributed to the ejection of relativistic bulk plasma from the nuclei of active galaxies, and accounts for the existence of large scale radio jets and lobes at large distances from the central regions of radio galaxies. Reports of radio jets and superluminal motion from galactic black hole candidate X-ray sources indicate that similar processes are operating in these sources. Observations of luminous, rapidly variable high-energy radiation from active galactic nuclei (AGNs) with the *Compton Gamma Ray Observatory* show directly that particles are accelerated to high energies in a compact environment.

The mechanisms which transform the gravitational potential energy of the infalling matter into nonthermal particle energy in galactic black hole candidates and AGNs are not conclusively identified, although several have been proposed. These include direct acceleration by static electric fields (resulting from, for example, magnetic reconnection), shock acceleration, and energy extraction from the rotational energy of Kerr black holes. The dominant acceleration mechanism(s) operating in the black hole environment can only be determined, of course, by a comparison of model predictions with observations.

The purpose of the work proposed for this grant was to investigate stochastic particle acceleration through resonant interactions with plasma waves that populate the magnetosphere surrounding an accreting black hole. Stochastic acceleration has been successfully applied to the problem of ion and electron energization in solar flares, and is capable of accounting for a wide range of both neutral and charged particle emissions. It is also a component in diffusive shock acceleration, since pitch-angle scattering (which is necessary for multiple shock crossings) is accompanied by diffusion in momentum space, which in turn yields a net systematic energy gain; however, stochastic energization will dominate the first-order shock process only in certain parameter regimes. Although stochastic acceleration has been applied to particle energization in the lobes of radio galaxies, its application to the central regions of AGNs has only recently been considered, but not in detail. We proposed to systematically investigate the plasma processes responsible for stochastic particle acceleration in black hole magnetospheres along with the energy-loss processes which impede particle energization.

To this end [see *Dermer, Miller, & Li, 1996*], we calculated acceleration rates and escape time scales for protons and electrons resonating with Alfvén waves, and for electrons resonating with whistlers. Assuming either a Kolmogorov or Kraichnan wave spectrum, accretion at the Eddington limit, magnetic field strengths near equipartition, and turbulence energy densities  $\sim 10\%$  of the total magnetic field energy density, we find that Alfvén waves accelerate protons to Lorentz factors  $\approx 10^4$ – $10^6$  before they escape from the system. Acceleration of electrons by fast mode and whistler waves can produce a nonthermal population of relativistic electrons whose maximum energy is determined by a competition with radiation losses.

Particle energization and outflow is not possible at lower accretion rates, magnetic field strengths, or turbulence levels due to dominant Coulomb losses. Increases in the accretion luminosity relative to the Eddington luminosity can trigger particle acceleration out of the thermal background, and this mechanism could account for the differences between radio-quiet and radio-loud active galactic nuclei. Observations of outflowing radio-emitting components following transient X-ray events in galactic X-ray novae and gamma-ray flares in blazars are in accord with this scenario.

In addition to this work, we also considered the “hot” topic of gamma-ray line emission from the Orion complex. Gamma-ray lines in the 3–7 MeV range were observed in 1994 from the direction of the Orion molecular cloud complex with the Compton Telescope (COMPTEL) on the *Compton Gamma Ray Observatory*. The location of the emission was centered at  $\ell = 208^\circ$ ,  $b = -18^\circ$ , and lies between the Orion A and Orion B HII regions at a distance of  $\approx 450$  pc. The measured flux in the 3–7 MeV regime is  $1.0(\pm 0.15) \times 10^{-4}$  photons  $\text{cm}^{-2} \text{s}^{-1}$ , corresponding to a  $\gamma$ -ray line luminosity of  $\approx 2 \times 10^{34}$  erg/s at the assumed distance.

We proposed [Miller & Dermer, 1995] that the observed  $\gamma$ -ray lines are produced by energetic ions that are stochastically accelerated by cascading Alfvén waves in the accretion plasma near a black hole. Stochastic particle acceleration by plasma wave turbulence in the accretion plasma near a black hole has been proposed as a mechanism to produce bulk electron/positron pair outflow through the production of a pair instability. Subsequent work [Dermer, Miller, & Li, 1995] demonstrated that stochastic proton and ion acceleration can also trigger particle outflow. Following this work, we show here that Alfvén waves, generated at large scales ( $\sim 10^2$  Schwarzschild radii) in a black hole accretion disk, are able to accelerate ions of progressively higher charge to mass ratios as they cascade to smaller wavelengths. The waves will therefore first encounter Fe. As long as the temperature of the accretion plasma is  $< 4 \times 10^6$  K, C and O will be accelerated before  $^4\text{He}$  and H. For all reasonable wave injection rates, the waves will be damped by C and O before reaching the lighter elements. In this way, energetic particle populations which are poor in H and He can be produced. The preferential acceleration of low  $Q/A$  species by cascading turbulence in the black hole accretion plasma could therefore explain the origin of the nuclear deexcitation lines observed with COMPTEL from the Orion region.

## 2. References

Listed below are the papers that were funded by this grant. Both papers are in refereed journals.

Miller, J. A., & C. D. Dermer, Abundance enhancements in black-hole accretion: application to  $\gamma$ -ray line observations of the Orion complex, *Astron. Astrophys.*, 298, L13, 1995.

Dermer, C. D., J. A. Miller, & H. Li, Stochastic particle acceleration near accreting black holes, *Astrophys. J.*, 456, 106, 1996.